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EFFECTS OF CONE VELOCITY AND SIZE ON SOIL PENETRATION RESISTANCE

Army Engineer Waterways Experiment Station
Vicksburg, Mississippi

December 1969

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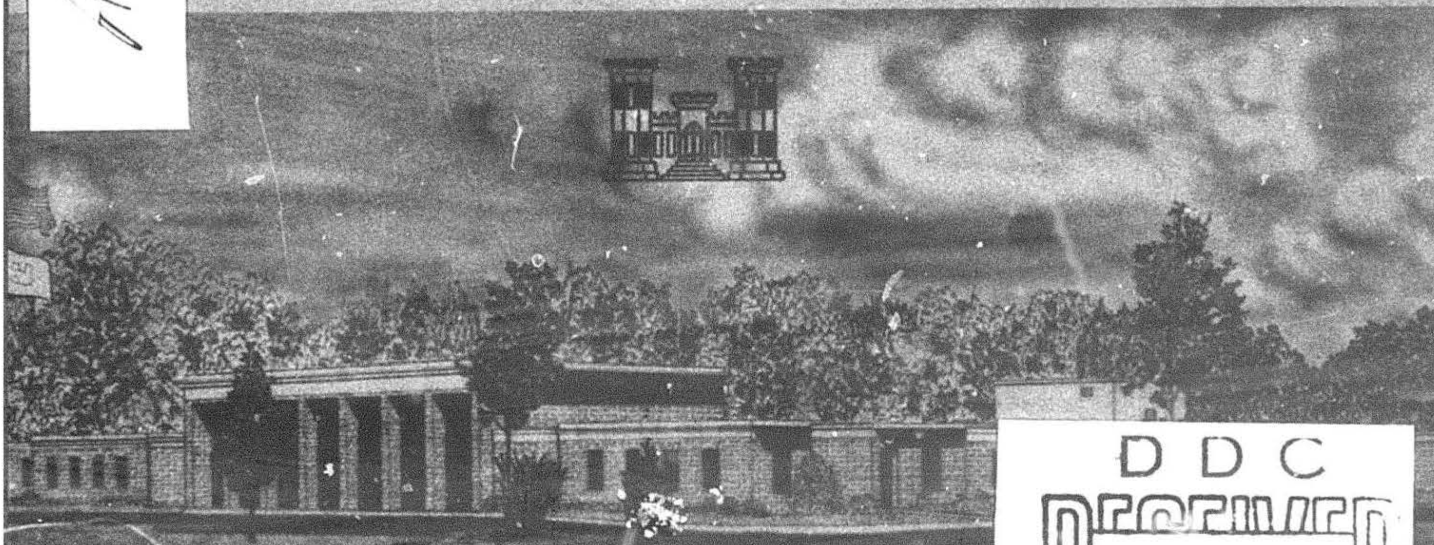
by

G. W. Turnage, D. R. Freitag



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13. ABSTRACT

Data show the cone penetration resistance of fine-grained soils is proportional to velocity and inversely proportional to cone diameter. An exponential equation based on the velocity-diameter ratio is developed to describe the interrelation. The exponent changes only slightly with soil type.

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Foreword

The study reported herein was conducted at the U. S. Army Engineer Waterways Experiment Station (WES) as a part of the vehicle mobility research program under DA Project 1T061102B52A, "Research in Military Aspects of Terrestrial Sciences," Task 01, "Military Aspects of Off-Road Mobility," under the sponsorship and guidance of the Research, Development and Engineering Directorate, U. S. Army Materiel Command.

Tests for this study were performed by personnel of the Mobility Research Branch, Mobility and Environmental Division, WES, under the general supervision of Messrs. W. J. Turnbull, W. G. Shockley, and S. J. Knight, and Dr. D. R. Freitag, and under the direct supervision of Mr. J. L. Smith. Messrs. G. W. Turnage and L. J. Lanz directed the study, and Mr. Turnage prepared this paper, which was presented at the 1969 Winter Meeting of the American Society of Agricultural Engineers.

COL John R. Oswalt, Jr., CE, and COL Levi A. Brown, CE, were Directors of WES during this study and the preparation of this paper. Messrs. J. B. Tiffany and F. R. Brown were Technical Directors.

Contents

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Summary

Data show the cone penetration resistance of fine-grained soils is proportional to velocity and inversely proportional to cone diameter. An exponential equation based on the velocity-diameter ratio is developed to describe the interrelation. The exponent changes only slightly with soil type.

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EFFECTS OF CONE VELOCITY AND SIZE ON SOIL PENETRATION RESISTANCE

by

G. W. Turnage and D. R. Freitag

In its off-road ground mobility research, the U. S. Army Engineer Waterways Experiment Station (WES) has found that standard cone index (soil penetration resistance obtained by using a particular combination of probe velocity, size, and shape) can be correlated with the performance of wheeled vehicles moving slowly (at 5 mph or less) in soil. Whether this correlation must be modified when high-speed vehicle performance is considered and, if so, to what extent is not known.

As a first step in answering this question, a study[1] was undertaken to define qualitatively the effects of penetration velocity and size of probes on penetration resistance measurements in fine-grained soils and to determine whether the parameters that describe the rate dependency of the penetration resistance of fine-grained soils are related to soil type.

Penetration tests were conducted with six sizes of 30-deg, right circular cones and three sizes of flat, circular plates (table 1) in three fine-grained soils--a fat clay, a lean clay, and a loessial silt--each tested at approximately 90 percent saturation. Soil strengths covered virtually the entire range relevant to problems of vehicle mobility (15 to 265 cone index).

Test Program

Vertical penetration tests

Vertical penetration tests were conducted in 15.5-in.-diam steel molds. All three soils were used for cone penetrations, but only the fat clay was used for the plates. Each probe was attached to a steel shaft of much smaller diameter than the base of the probe; the shaft, in turn, was connected to a force-measuring load cell (fig. 1). The shafts were strong enough to ensure a straight alignment and small enough to prevent soil drag.

Three low-speed penetrometers--a converted CBR machine, a mechanical penetrometer, and a modified triaxial machine--were used for constant-velocity penetrations, which ranged from 0.090 to 825 in./min. For each velocity within this range, repeatability to an accuracy on the order of 2 percent was achieved.

At least two penetrations were made for each combination of probe size, penetration velocity, and soil consistency, so that an average value relatively unaffected by soil uniformities could be obtained. Also two or three standard penetrations were made in each mold (i.e. with the 0.5-sq-in. cone at a velocity of 72 in./min). Care was taken that each penetration be unaffected by an adjacent one, or by proximity to either the sidewall or the bottom of the container. Experience has shown that this can be achieved in soft, fine-grained soil when a minimum spacing of twice the diameter of the largest cone is maintained.[2]

Tests with the plates were conducted only with the mechanical penetrometer. The first three penetrations in each test were made with the 0.5-sq-in. cone to obtain a standard value of penetration resistance.

Penetration resistance values for both cones and plates were the averages computed from readings taken at 0.5-in. vertical increments to a 2-in. depth, beginning at a point where the relation of penetration resistance to depth had stabilized, i.e. at a depth equal to the cone height or the plate base diameter.

Horizontal penetration tests

The horizontal penetration tests were conducted with only fat clay in the large (2.7- by 5.3- by 27.0-ft) test bins of the WES mobility facility.[3] Only the 0.5-, 1.0-, and 2.0-sq-in. cones were used.

Maximum penetration velocity capability was increased from 825 to 10700 in./min (i.e. to 14.8 ft/sec) by mounting a special assembly on the forward face of the dynamometer test carriage (fig. 2) and penetrating the soil-bin test section horizontally. In the assembly, a hollow outer shaft protected a specially machined inner shaft, which was threaded to receive the cones and instrumented with strain gages to record only the force transmitted to its leading face by the cone. Calibration tests showed the axial loads over the full range encountered subsequently were recorded to an accuracy of ±2 percent. Also, it was determined that forces to 12 lb applied perpendicularly to the shaft were not picked up by the strain gages, indicating that any nonaxial loads caused by shaft misalignment were not recorded.

After a test section was constructed, the soil surface was planed and vertical penetrations were made with the 0.5-sq-in. cone at 72 in./min velocity at 5-ft horizontal intervals along the length of the section. Each horizontal penetration passed through the locations of all these vertical penetrations at a depth of 7 in. beneath the soil surface. Velocity was programmed to increase linearly to a maximum value, at which time the cone assembly passed through the far open end of the test section into air. Five tests were run at maximum velocities ranging from 12.0 to 14.8 ft/sec. The standard cone penetration resistance value for a given test section was the average of all readings from the vertical penetrations, taken at the depth of the horizontal penetration.

Effects of Soil Consistency and Penetration Velocity

Data from vertical penetrations with the 0.5-sq-in. cone in 13 mold test sections of fat clay (fig. 3) show that penetration resistance increases with penetration velocity, that the same general curve shape describes this relation for a wide range of soil consistencies, and that the absolute change in indicated soil strength increases as the value of standard penetration resistance increases. These observations suggested that all the data in fig. 3 might be described by one curve if each value of penetration resistance (C_x*) were expressed as a ratio of the standard value (C_s).

*See Notation at end of text.

The resulting penetration resistance ratios, C_{xs}, are plotted in fig. 4. All the data from tests conducted in fat clay with the 0.5-sq-in. cone are shown. There is a strong tendency for the points to group about a single line. This result was very useful in subsequent analyses, since data from all soil strength levels could be related to a single curve, eliminating the need to create exactly replicate samples for the several phases of the test program.

The data are presented in logarithmic form in fig. 5b. A straight line of slope 0.105 passing through the coordinates (1.0,3.23) that delineate the standard test conditions was judged to represent the data adequately for penetration velocities larger than about 2.6 in./min. Below 2.6 in./min, the values of C_{xs} are nearly constant and average 0.707. Such a region over which the penetration resistance did not change with speed appeared at the slow-speed end of the data range in tests with other soils also. The velocity at which the speed effect became apparent has been termed the threshold velocity. This feature will be referred to again and discussed more fully in the context of the effect of soil type on the test results. The primary data analysis, however, is concerned only with the data obtained at velocities greater than the threshold velocity.

Effects of Cone Size

The logarithmic relation of soil penetration resistance ratio versus penetration velocity for each of the six sizes of cones tested in fat clay is presented in fig. 5. The shape of the central line in each plot is similar to that for the 0.5-sq-in. cone (fig. 5b), i.e. a horizontal line through an extended range of very low penetration velocities, followed by a straight line of slope 0.105.

The influence of cone size on penetration resistance ratio is accounted for by dividing penetration velocity, V_x, by cone diameter, d_x. This operation collapsed the family of curves of fig. 5 to the single curve in fig. 6a. This latter relation was then changed to nondimensional form by dividing each value of $(V/d)_x$ by

$(V/d)_s$, the constant velocity-to-diameter ratio associated with a standard penetration resistance, $\frac{72.0 \text{ in./min}}{0.798 \text{ in.}} = 90.2 \frac{\text{in./min}}{\text{in.}}$. This produced the nondimensional relation $C_{xs} = 1.0 \left[(V/d)_{xs}\right]^{0.105}$, which is presented in fig. 6b. Note that this last relation is normalized with respect to C_s and $(V/d)_s$, since the denominators of the abscissa and ordinate variables describe a standard penetration resistance.

The equation expressed in the preceding paragraph was based on a visual judgment of the best fit correlation line for data believed to lie above the threshold velocity. To gain more confidence of the value and precision of this equation, statistical regression lines were developed by an iterative process in which successive approximations of the threshold values were obtained and regression lines computed for all data that exceeded these thresholds. Because both of the two variables are ratios to a standard, the correlation line should pass through the identity coordinates (1.0,1.0). In most instances, the statistical line approached these values quite closely; in all cases, the equations finally used placed the line through the identity coordinates, but at the slope determined from the regression analysis. The equations fit the data well and are not greatly different from the visually located lines. The final relation, together with the data considered to lie above the threshold velocity, is shown in fig. 7.

Effects of Probe Shape

Fifty-four plate penetration tests were conducted at six velocities (1, 3, 10, 30, 72, and 100 in./min) in mold samples of fat clay at three soil consistencies (20, 40, and 80 standard penetration resistance). Results were analyzed to determine the influence of the shape of the leading face (i.e. 180° or 30°) of the penetrating element on soil penetration resistance.

A central line of equation $P_{xs} = 0.91 \left[(V/d)_{xs}\right]^{0.056}$ was obtained through a least-squares curve-fitting technique to describe the logarithmic relation in fig. 8.

The values of P_{xs} showed no apparent tendency to level off at the lower end of the curve, indicating that threshold velocities of the plates in fat clay are smaller than the minimum 1 in./min of this study. The slope of the central line (0.056) is smaller than that of the corresponding relation for cones (0.092). Therefore, with increasing penetration velocity, the penetration resistance of fat clay increases more slowly for flat plates than for cones, at least over the range of penetration velocities of this study. The extended central line in fig. 8 passes through coordinates (1.00,0.91), indicating that fat clay offers less penetration resistance to a flat plate than to a 30-deg cone of the same circular base area at standard penetration velocity (72 in./min). The central line in fig. 8 intersects the one in fig. 7 at (0.0726,0.786), as shown in fig. 9; so the penetration resistance of fat clay is greater for plates than for cones at velocity/diameter ratio values less than 0.0726, while the opposite is true at values greater than 0.0726.

Why the apparent viscosity of the soil should change as a consequence of changing the shape of the penetrating object is not clear. It might be expected that the absolute value of the resistance at any velocity would be different, but not the rate at which it changed in response to a velocity change. Possibly the total volume of soil undergoing strain when penetrated by one probe shape changes with velocity more than when penetrated by another. Since the data presented here are very limited in scope, the results cannot be considered conclusive. Further tests are obviously needed to study this point.

Effects of Soil Type

The data from cone penetration tests in the other two test soils, a lean clay and a loessial silt, were analyzed in the same manner described for fat clay. The value of cone penetration resistance ratio remained essentially constant over a wide range of low values of velocity/diameter ratio for each cone tested in these two soils (fig. 10).

In general, the absolute velocity at which the threshold condition becomes apparent appears to be highest for the smallest cone sizes (see figs. 5 and 10). Also, the highest absolute velocity at which a threshold appears for any one cone size is greatest for the silt, slightly less for the lean clay, and considerably less for the fat clay (fig. 11). These observations suggest that local drainage of the water from the soil being stressed by the penetrator has modified the viscous-type rate-dependent response of higher velocity ranges. The greatest amount of water would migrate at the slowest speed from the most pervious soil and would be effective sooner in the smallest stressed volumes. Since water loss causes the soil to be stronger, these conditions are in accord with the test results.

At values of velocity/diameter ratio greater than the threshold value, 90 percent saturated lean clay and silt behave in a manner very similar to that of fat clay (see fig. 12). In this range of values, the relation among cone size, penetration velocity, soil consistency, and soil penetration resistance for the three test soils is described by an equation of form $C_{xs} = 1.0 \left[(V/d)_{xs}\right]^n$. This suggests that the flow characteristics of a wide range of fine-grained soils can be estimated if a relation can be found between n and some other measured soil property. Unfortunately, data from the three test soils of this study are insufficient to establish such a relation, but it is significant that n is not greatly different from 0.100 for any of these soils.

Horizontal Penetration Test Results

Data from the horizontal penetration tests cluster about the same central line established for the results of the vertical penetration tests (fig. 13a), indicating that the constant depth at which the horizontal penetrations were made was sufficiently large to eliminate noticeable boundary effects, and that the direction of cone penetration in fat clay has negligible influence on penetration resistance.

The same relation is shown in arithmetic form in fig. 13b. The data seem more scattered here and appear to tend toward values of cone penetration resistance ratio somewhat larger than the central line, for values of velocity/diameter ratio larger than about 40. This divergence is thought to be caused by inertial forces, whose contribution to overall penetration resistance becomes noticeable only after relatively large penetration velocities are achieved. Some simple calculations indicate that the increment of resistance is approximately of the proper magnitude, but the very limited amount of high-speed test data allowed little opportunity to test this hypothesis further. Tests are needed at penetration velocities much greater than those of this study to determine quantitatively the effects of inertia on total penetration resistance.

Notation

C_s	Average standard soil penetration resistance of a test section obtained by penetrating the soil at 72 in./min with a 30-deg-apex-angle, right circular cone and dividing the average soil penetration resistance (in pounds) by the base area of the cone (0.5 sq in.).
C_x	Average soil penetration resistance, a measure obtained in the same way as C_s, except that no restriction is placed on the size of the cone or the penetration velocity used.
C_{xs}	Nondimensional penetration resistance ratio obtained by using cone only.
d_s	Base diameter of standard cone, 0.798 in.
d_x	Base diameter of any cone or plate.
P_{xs}	Nondimensional penetration resistance ratio obtained by using the standard cone (0.5-sq-in. base area) and any size of flat, circular plate.
V_s	Standard penetration velocity, 72 in./min.
V_x	Any penetration velocity (of either a cone or a plate).
$(V/d)_s$	Constant penetration velocity-to-base diameter ratio.
$(V/d)_x$	Penetration velocity-to-base diameter ratio of any cone or of any plate (may take on any value).
$(V/d)_{xs}$	Ratio of $(V/d)_x$ to $(V/d)_s$.

References

1. Turnage, G. W., "Measuring Soil Properties in Vehicle Mobility Research; Effects of Velocity, Size, and Shape of Probes on Penetration Resistance of Fine-Grained Soils," Technical Report No. 3-652, Report 3 (being prepared for publication), U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

2. Green, A. J., and Knight, S. J., "Effects of Mold Size and Other Factors on Laboratory Cone Index Measurements," Miscellaneous Paper No. 4-327, Mar 1959, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

3. McRae, J. L., Powell, C. J., and Wismer, R. D., "Performance of Soils Under Tire Loads; Test Facilities and Techniques," Technical Report No. 3-666, Report 1, Jan 1965, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

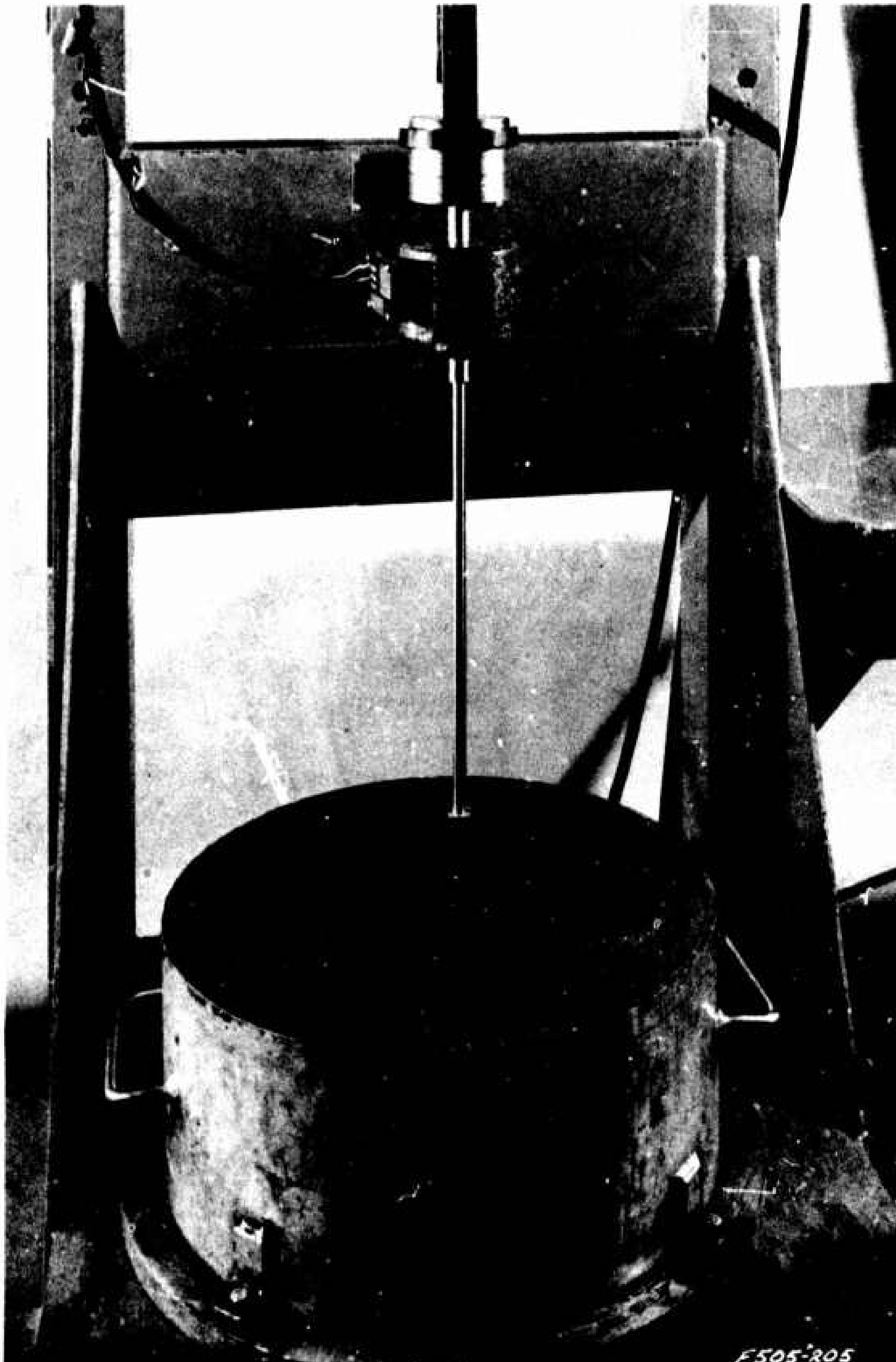


Fig. 1. Test arrangement for vertical penetrations

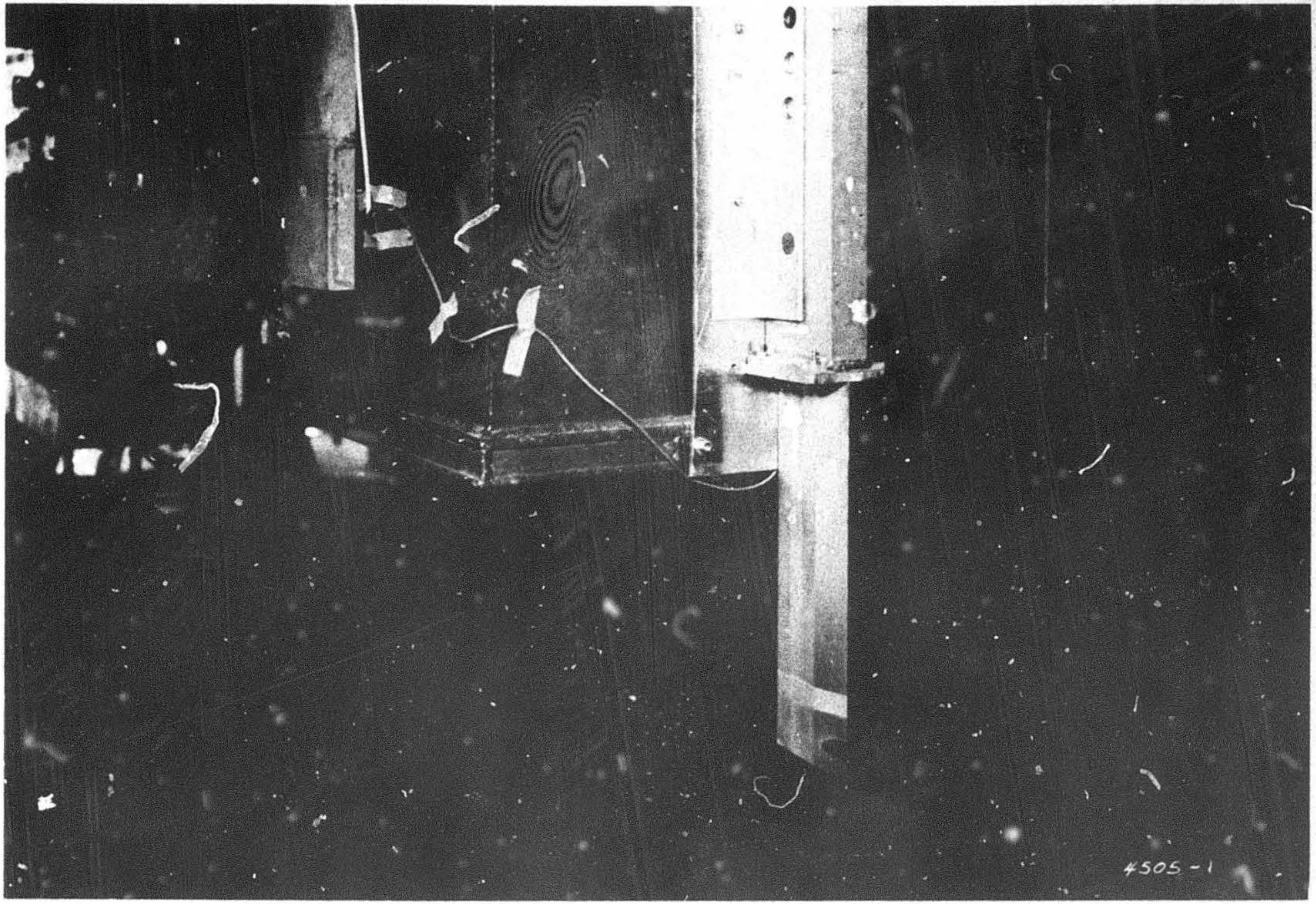
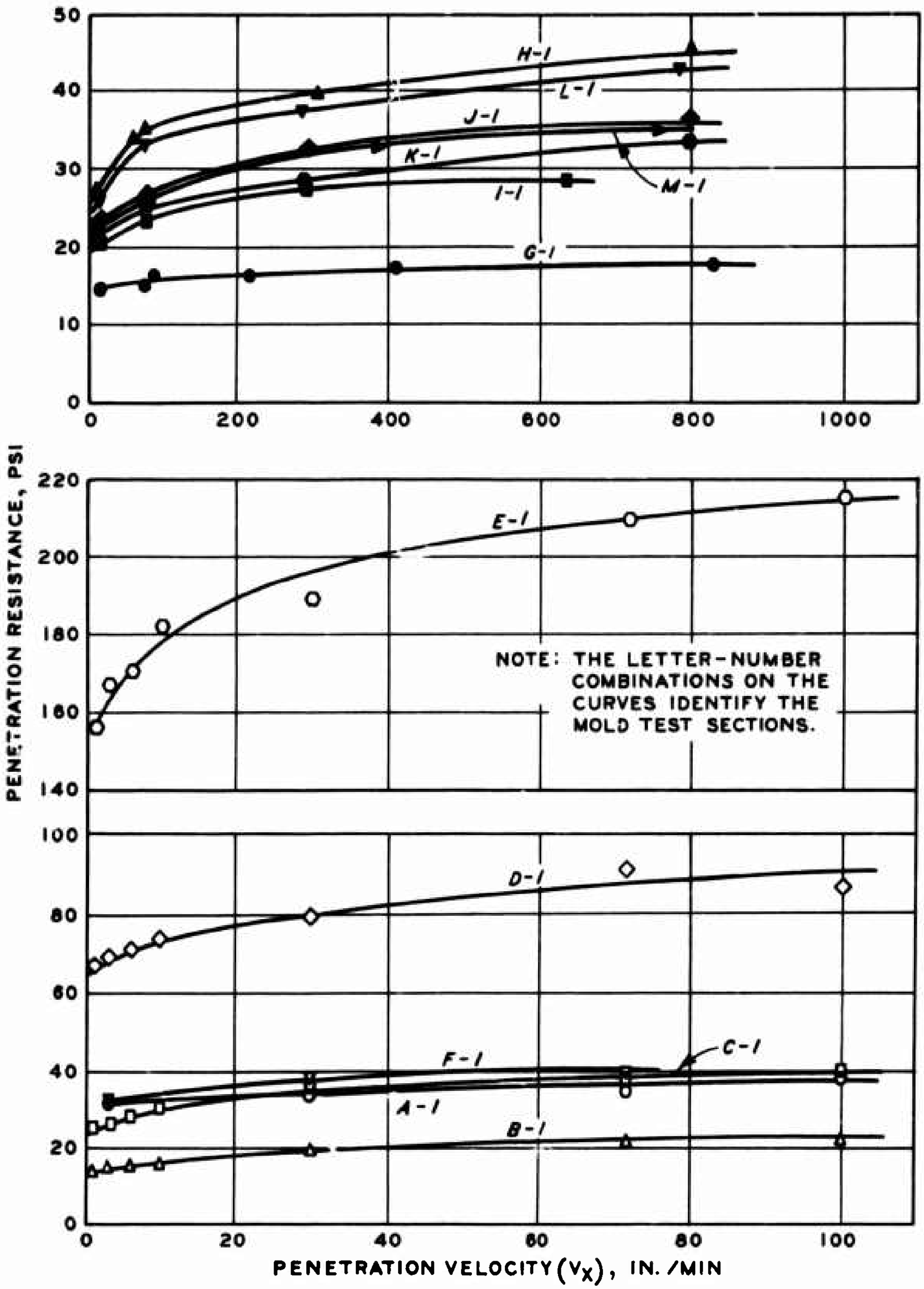
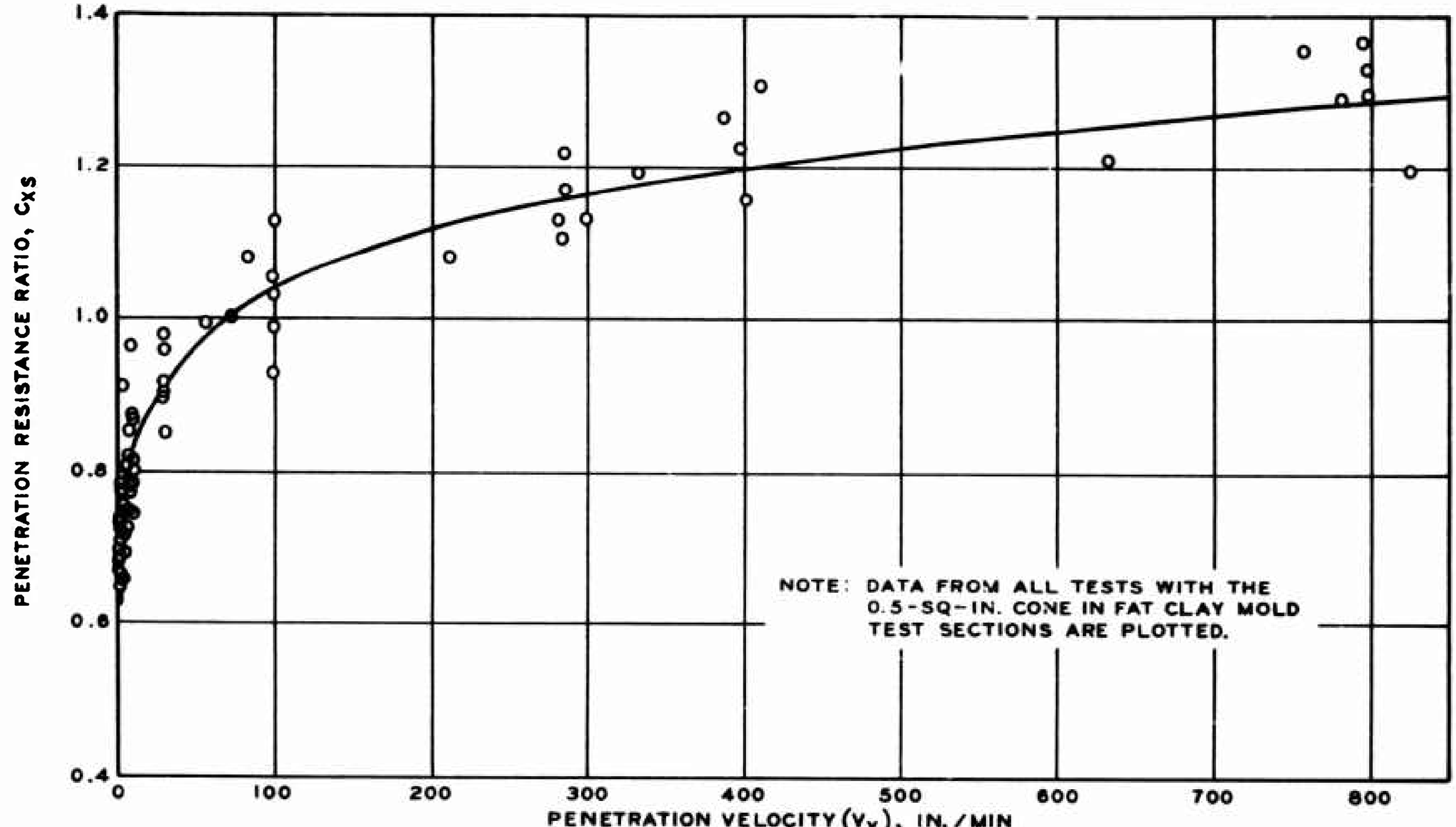


Fig. 2. Special assembly for horizontal penetrations



EFFECT OF VELOCITY ON PENETRATION RESISTANCE IN FAT CLAY
0.5-SQ-IN.-BASE-AREA CONE

Fig. 3

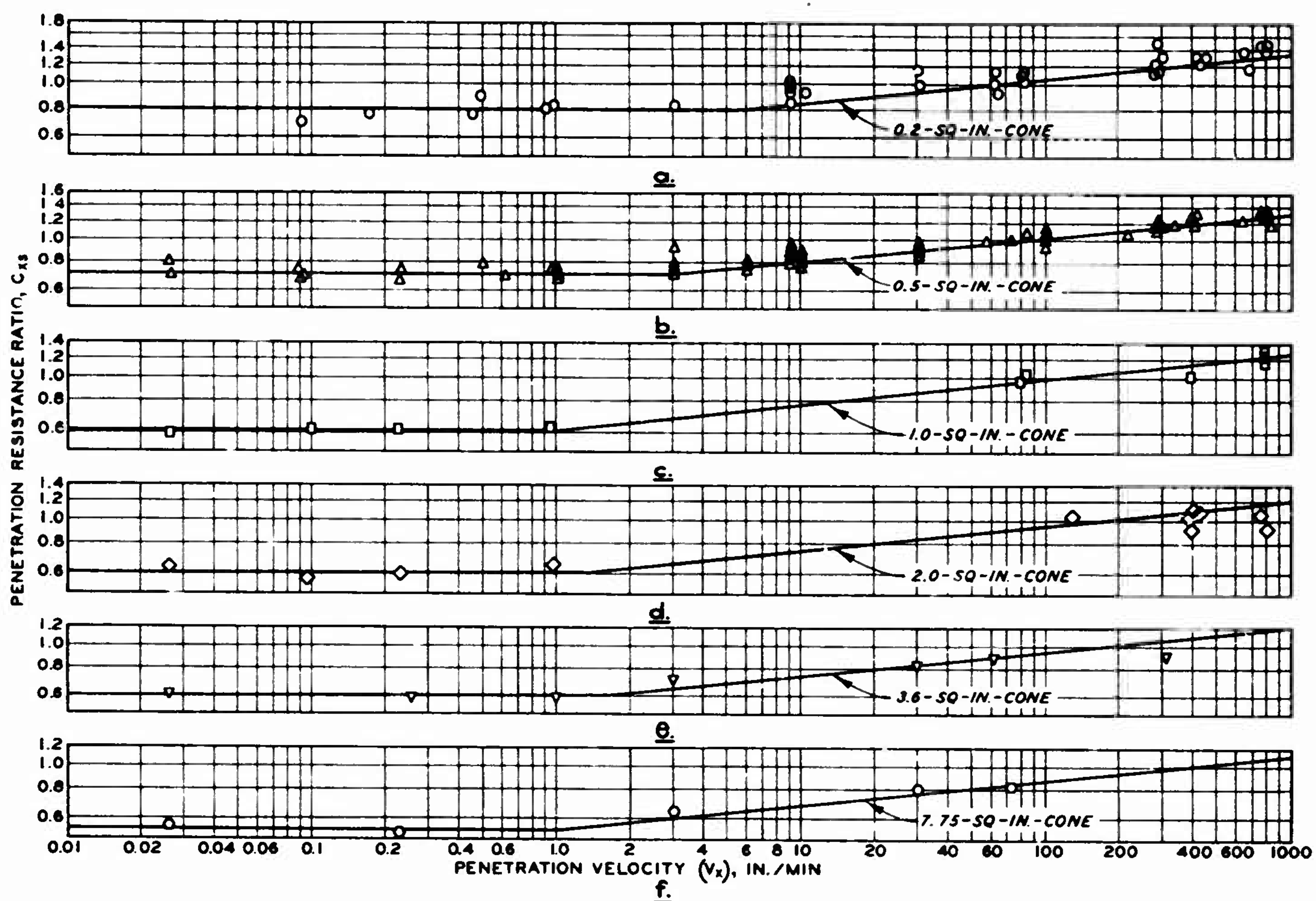


EFFECT OF VELOCITY ON PENETRATION RESISTANCE RATIO IN FAT CLAY

(FIRST TRIAL FIT OF THE TEST DATA)

0.5-SQ-IN.-BASE-AREA CONE

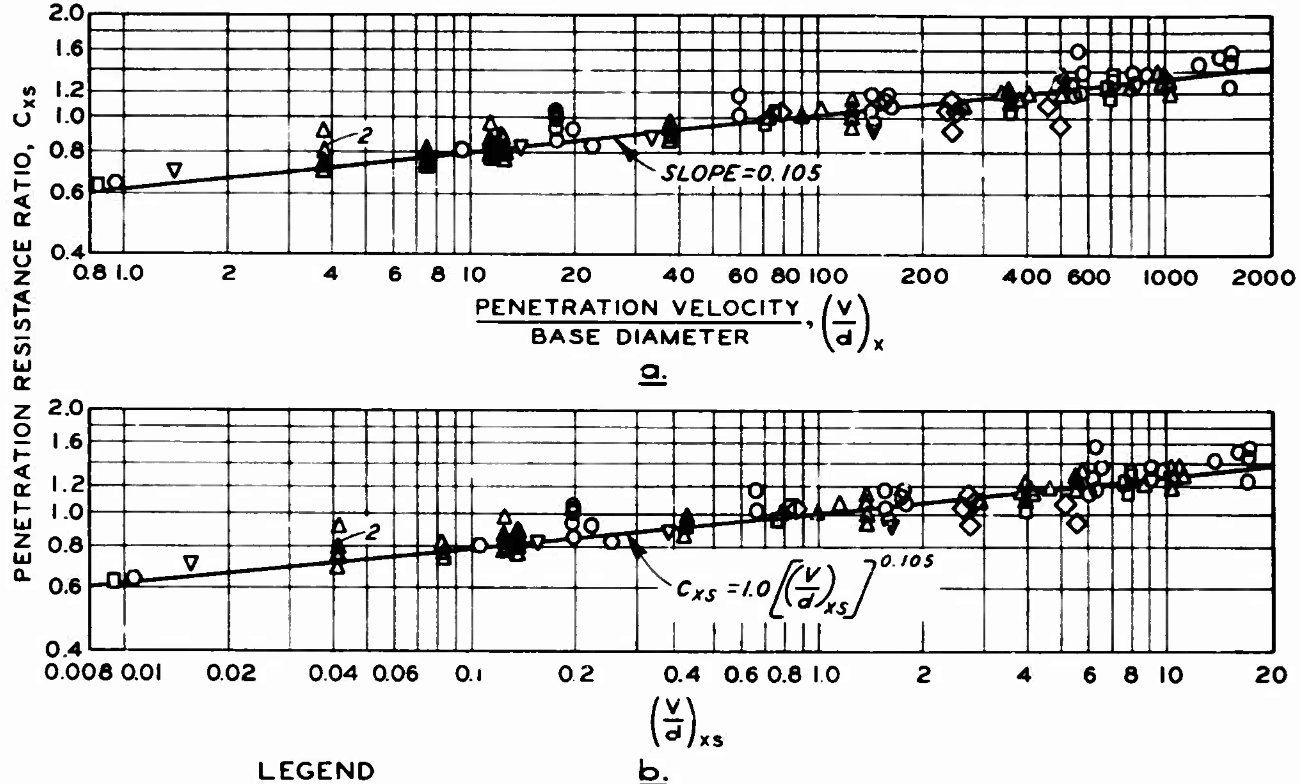
Fig. 4



NOTE: THE SLOPE OF THE NONHORIZONTAL PORTION OF EACH LINE SHOWN ABOVE IS 0.105.

EFFECT OF VELOCITY ON PENETRATION RESISTANCE RATIO IN FAT CLAY
(LOG PLOT)
(FIRST TRIAL FIT OF THE TEST DATA)
SIX CONE SIZES

Fig. 5

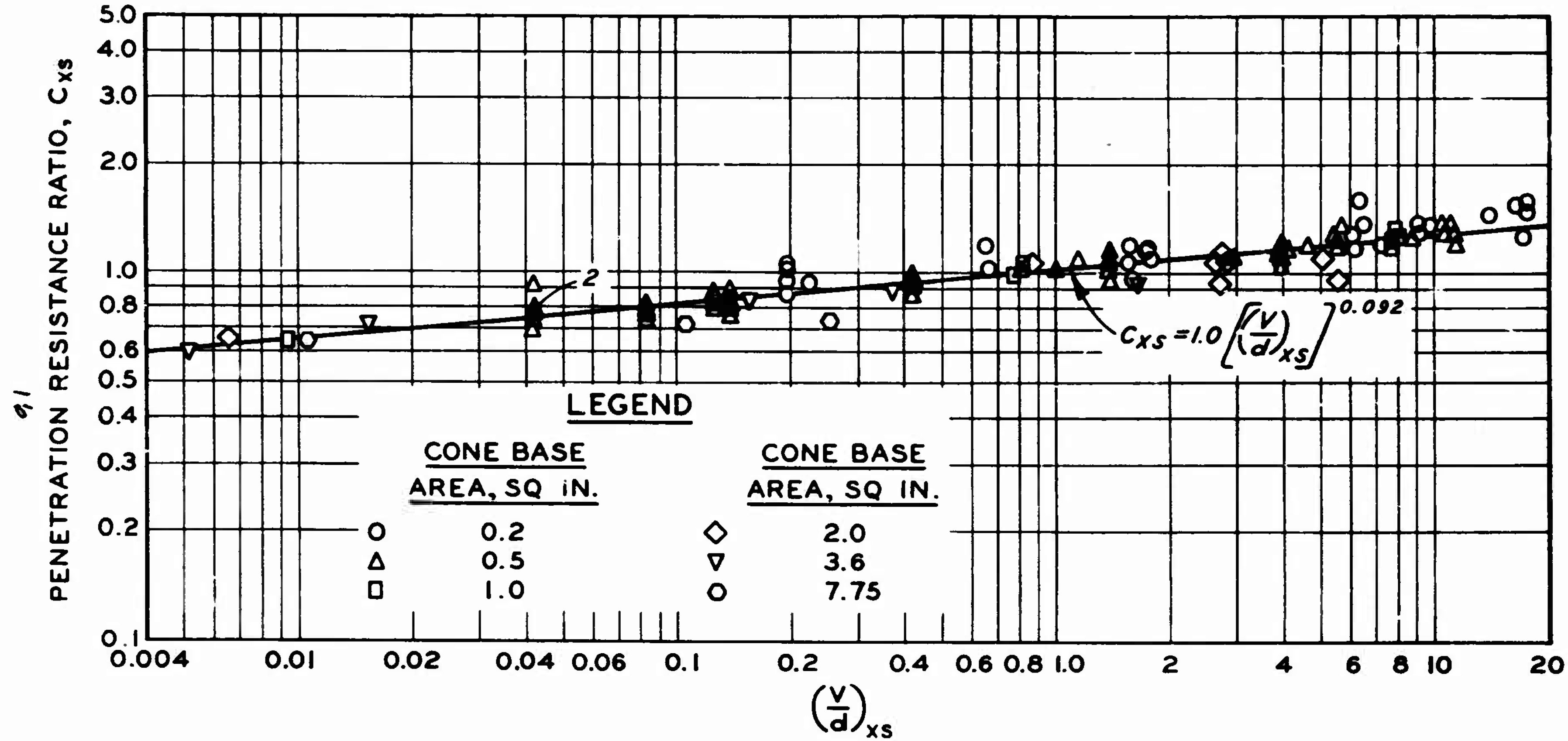


LEGEND

	CONE BASE AREA, SQ IN.		CONE BASE AREA, SQ IN.
○	0.2	◇	2.0
△	0.5	▽	3.6
□	1.0	o	7.75

INFLUENCE OF VELOCITY AND CONE DIAMETER ON PENETRATION RESISTANCE RATIO IN FAT CLAY
(LOG PLOTS)
FIRST TRIAL FIT OF THE TEST DATA, SIX CONE SIZES

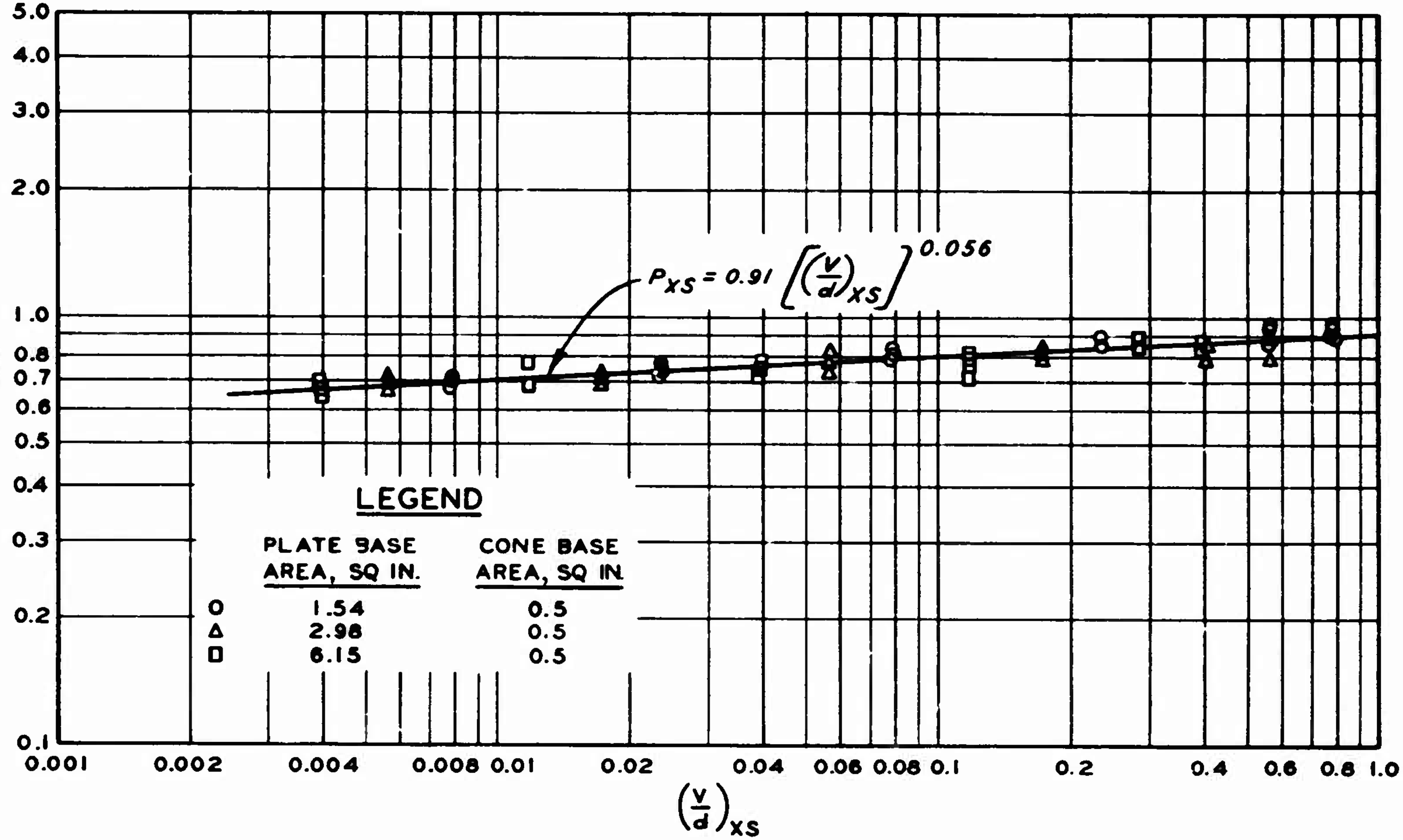
Fig. 6



INFLUENCE OF VELOCITY/CONE DIAMETER RATIO ON PENETRATION RESISTANCE RATIO
(LOG PLOT)

FINAL DESCRIPTION OF THE TEST DATA
TESTS OF FAT CLAY SAMPLES IN MOLDS

Fig. 7

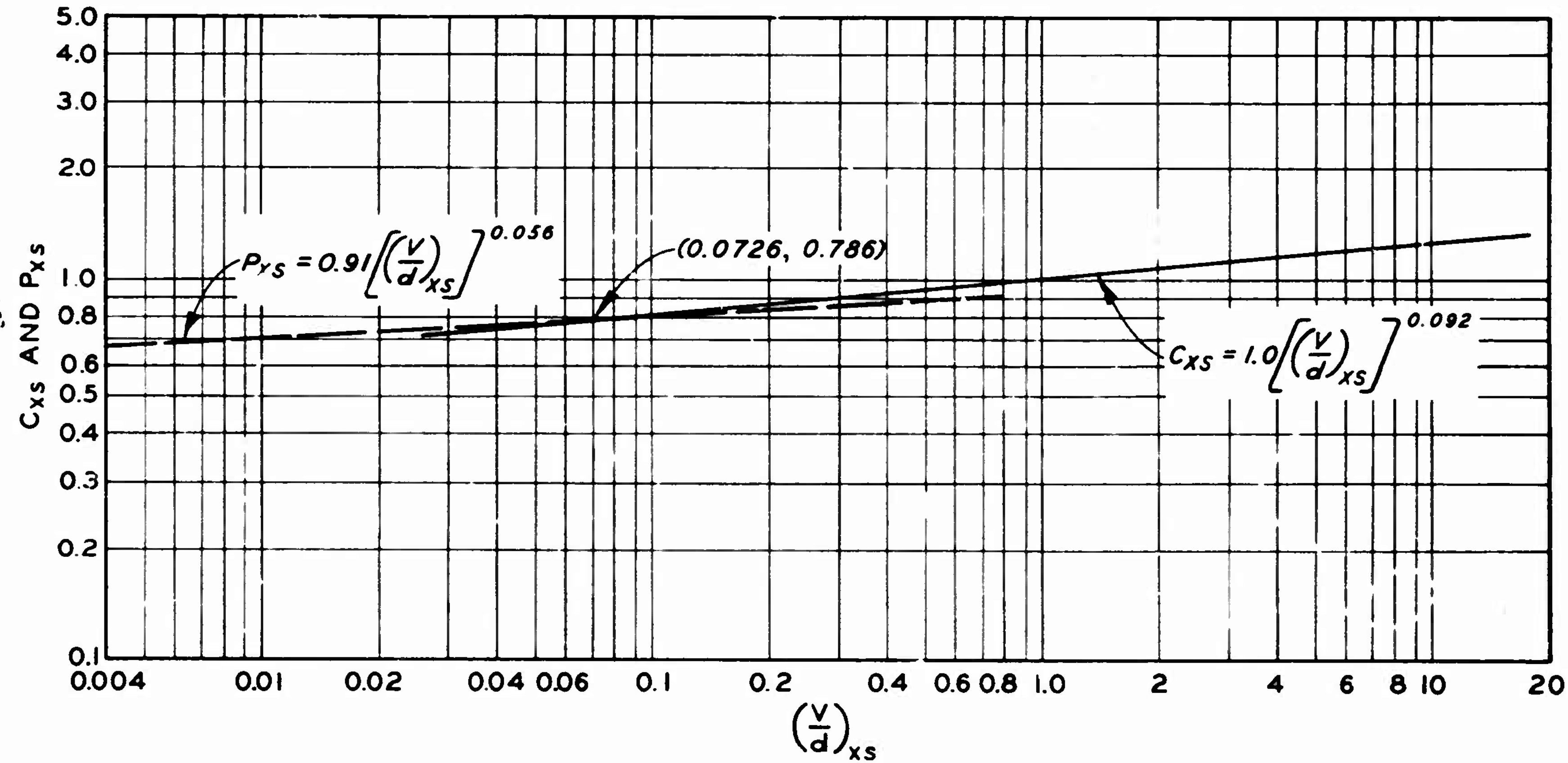


INFLUENCE OF PROBE SHAPE, SIZE, AND VELOCITY ON PENETRATION RESISTANCE OF FAT CLAY

(LOG PLOT)

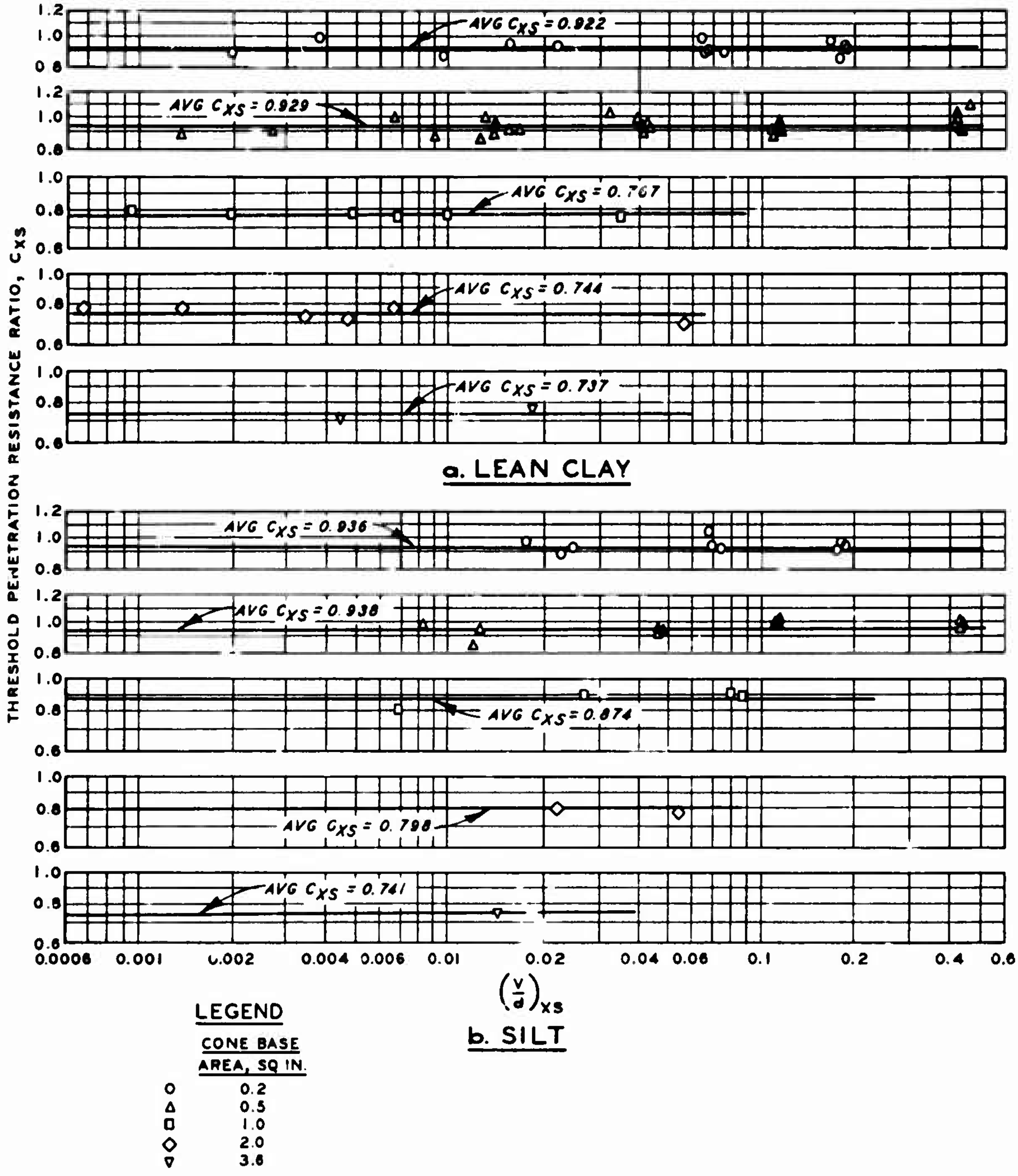
THREE SIZES OF PLATES, ONE SIZE CONE

Fig. 8



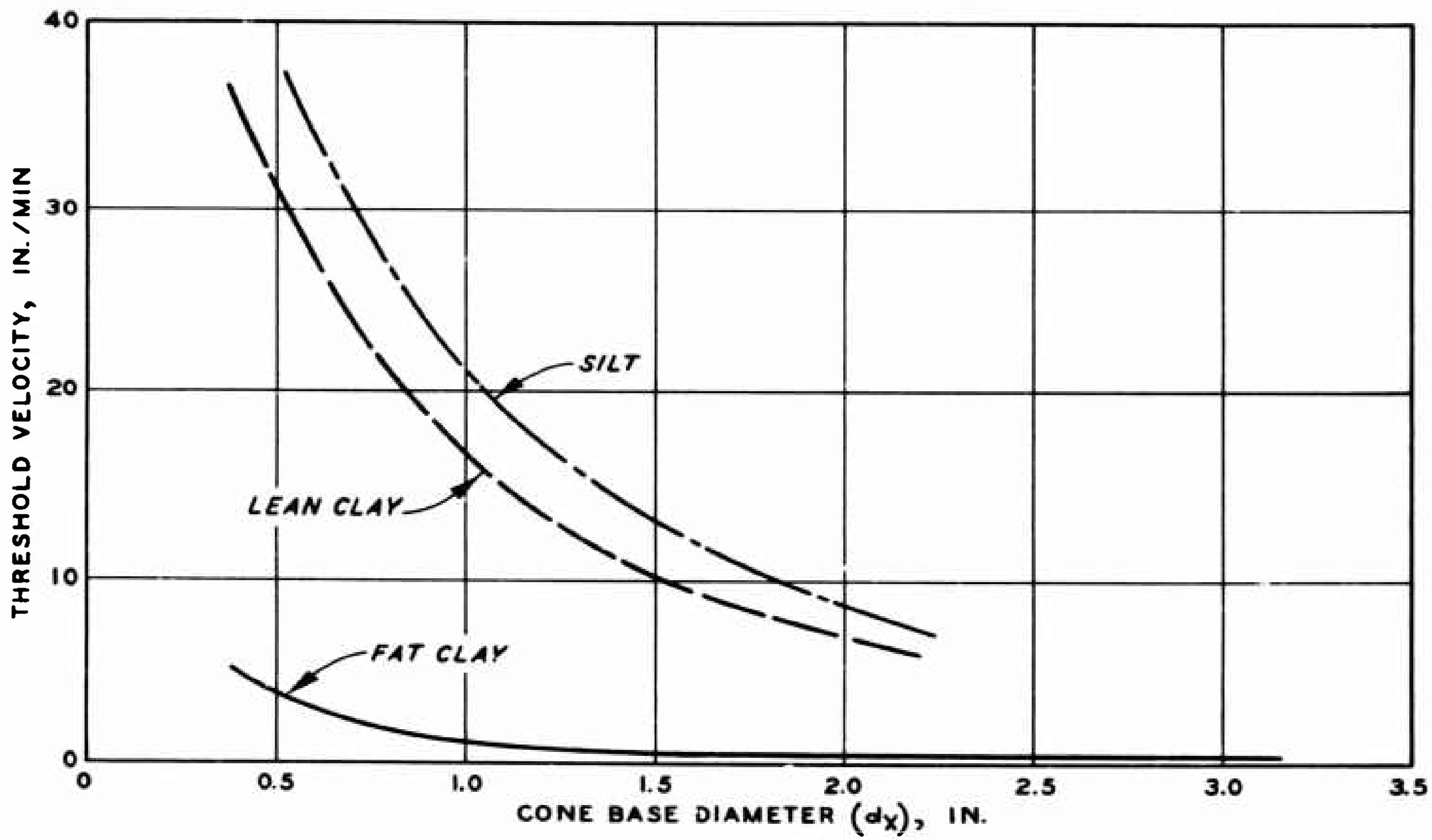
VISCOUS BEHAVIOR OF FAT CLAY WHEN PENETRATED
(a) BY A CONE AND (b) BY A FLAT PLATE

Fig. 9



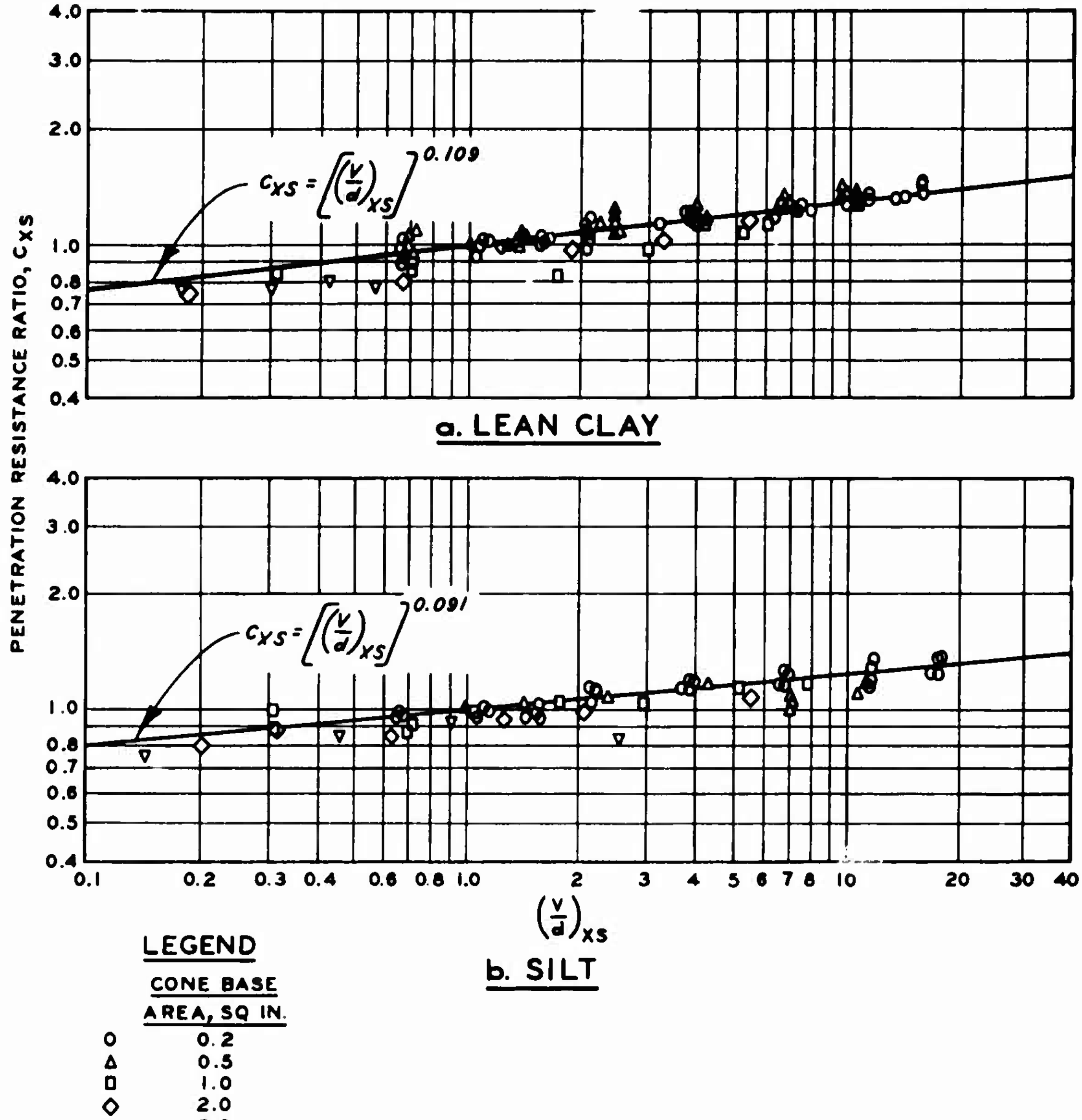
DETERMINATION OF THRESHOLD PENETRATION RESISTANCE RATIO VALUES
(LOG PLOT)
90-PERCENT-SATURATED LEAN CLAY AND SILT
FIVE CONE SIZES

Fig. 10



INFLUENCE OF CONE BASE DIAMETER ON THRESHOLD PENETRATION VELOCITIES OF THREE FINE-GRAINED SOILS

Fig. 11

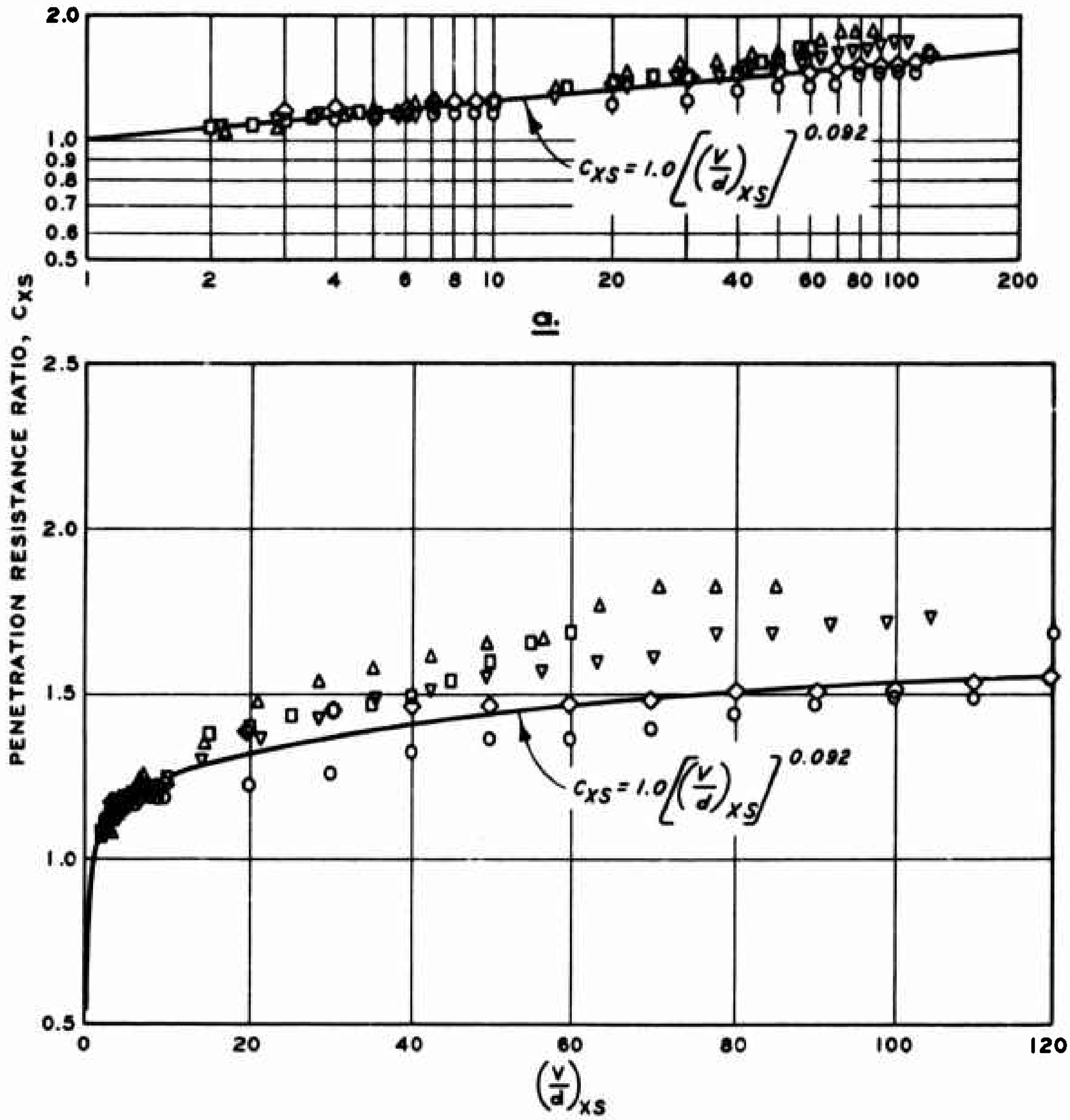


INFLUENCE OF VELOCITY/CONE DIAMETER RATIO ON PENETRATION RESISTANCE RATIO

(LOG PLOT)

90-PERCENT-SATURATED LEAN CLAY AND SILT

FIVE CONE SIZES



LEGEND

b.

	TEST NO.	CONE BASE AREA, SQ IN.	C_S, PSI
○	1	0.5	26.0
△	2	1.0	20.0
□	3	2.0	23.7
◇	4	0.5	48.6
▽	5	1.0	43.1

INFLUENCE OF PENETRATION VELOCITY/CONE DIAMETER RATIO ON PENETRATION RESISTANCE RATIO IN FAT CLAY

(LOG AND ARITHMETIC PLOTS)

HORIZONTAL PENETRATION TESTS

TEST VELOCITIES UP TO 14.8 FT/SEC

Fig. 13

Table 1

Pertinent Data for Test Probes

Cones			Plates	
Base Area Sq In.	Base Diam In.	Length In.	Base Area Sq In.	Base Diam In.
0.20	0.504	0.940	1.54	1.400
0.50	0.798	1.485	2.98	1.950
1.00	1.128	2.105	6.15	2.800
2.00	1.596	2.978		
3.60	2.141	3.995		
7.75	3.141	5.861		